# UNIT 2

# ATMOSPHERIC PHYSICS

## FOREWORD

The science of physics is devoted to finding, defining, and reaching solutions to problems. It is the basic science that deals with motion, force, and energy. Physics, therefore, not only breeds curiosity of one's environment, but it provides a means of acquiring answers to questions that continue to arise. Atmospheric physics is a branch of physical meteorology that deals with a combination of dynamic and thermodynamic processes that account for the existence of numerous atmospheric conditions.

To understand the weather elements and to analyze meteorological situations you must know how to apply the fundamental principles of physics and atmospheric physics. This does not mean that you must be able to understand all of the complicated theories of meteorology. It does mean, however, that you should have a fair working knowledge of elementary physics. You should learn how to apply the rules of physics to understand the atmosphere. This is necessary to perform your duties as an Aerographer's Mate in a creditable manner.

A forecaster's understanding of mathematics becomes important to an ever-increasing degree. Your progression must include a basic mathematical knowledge of ratio, proportion, interpolation, percentage, and trigonometric functions of a right triangle. As you move further into the field of meteorology, you will find it helpful to increase your mathematical knowledge by referring to the following training manuals: *Mathematics, VOL 1,* NAVEDTRA 10069-D, *Mathematics, Vol. 2,* NAVEDTRA 10071-B, or *Mathematics, Vol. 3,* NAVEDTRA 10073-A. Additional sources of information include the many mathematical courses offered by colleges. Information on these courses and manuals may be obtained from your Educational Service Office (ESO).

Unit 2 covers the following lessons: Lesson 1, Motion; Lesson 2, Matter; Lesson 3, Gas Laws; and Lesson 4, Atmospheric Energy.

## UNIT 2—LESSON 1

# MOTION

OVERVIEW

Describe the laws of motion and determine how motion is affected by external forces.

OUTLINE

Terms

Laws of Motion

Work

Energy

Force

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### MOTION

Any general discussion of the principles of physics must contain some consideration of the way in which mass, force, and motion are related. In physics, the laws of motion state that an object at rest never starts to move by itself; a push or a pull must be exerted on it by some other object. This applies to weather also. Weather has many complex motions, both in the vertical and horizontal planes. To fully understand how and why weather moves, you must have a basic knowledge of motion and those external forces that affect motion.

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**Learning Objective: Describe the laws of motion and determine how motion is affected by external forces.**

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### TERMS

In dealing with motion several terms should be defined before you venture into the study of motion. These terms are inertia, speed, direction, velocity, and acceleration.

#### Inertia

An object at rest never moves unless something or someone moves it. This is a property of all forms of matter (solid, liquid, or gas). Inertia, therefore, is the property of matter to resist any change in its state of rest or motion.

#### Speed

Speed is the *rate* at which something moves in a given amount of time. In meteorology, speed is the term that is used when only the rate of movement is meant. If the rate of movement of a hurricane is 15 knots, we say its speed is 15 knots per hour.

#### Direction

Direction is the line along which something moves or lies. In meteorology, we speak of direction as *toward* or the direction *from* which an object is moving. For example, northerly winds are winds COMING FROM the north.

#### Velocity

Velocity describes both the *rate* at which a body moves and the *direction* in which it is traveling. If the hurricane, with its speed of 15 knots per hour, is described as moving westward, it now has velocity—both a rate and direction of movement.

### Acceleration

This term applies to a rate of change of the speed and/or the velocity of matter with time. If our hurricane, which is presently moving at 15 knots, is moving at 18 knots 1 hour from now and 21 knots 2 hours from now, it is said to be accelerating at a rate of 3 knots per hour.

## LAWS OF MOTION

Everything around us is in motion. Even a body supposedly at rest on the surface of Earth is in motion because the body is actually moving with the rotation of Earth; Earth, in turn, is turning in its orbit around the Sun. Therefore, the terms *rest* and *motion* are relative terms. The change in position of any portion of matter is motion. The atmosphere is a gas and is subject to much motion. Temperature, pressure, and density act to produce the motions of the atmosphere. These motions are subject to well-defined physical laws. An explanation of Newton's laws of motion can help you to understand some of the reasons why the atmosphere moves as it does.

### Newton's First Law

Sir Isaac Newton, a foremost English physicist, formulated three important laws relative to motion. His first law, the law of inertia, states, "every body continues in its state of rest or uniform motion in a straight line unless it is compelled to change by applied forces." Although the atmosphere is a mixture of gases and has physical properties peculiar to gases, it still behaves in many respects as a body when considered in the terms of Newton's law. There would be no movement of great quantities of air unless there were forces to cause that movement. For instance, air moves from one area to another because there is a force (or forces) great enough to change its direction or to overcome its tendency to remain at rest.

### Newton's Second Law

Newton's second law of motion, force, and acceleration states, "the change of motion of a body is proportional to the applied force and takes place in the direction of the straight line in which that force is applied." In respect to the atmosphere, this means that a change of motion in the atmosphere is determined by the force acting upon it, and that change takes place in the direction of that applied force.

From Newton's second law of motion the following conclusions can be determined:

1. If different forces are acting upon the same mass, different *accelerations* are produced that are proportional to the forces.
2. For different masses to acquire equal *acceleration* by different forces, the forces must be proportional to the masses.
3. Equal forces acting upon different masses produce different *accelerations* that are proportional to the masses.

### Newton's Third Law

Newton's third law of motion states, "to every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts." In other words forces acting on a body originate in other bodies that makeup its environment. Any single force is only one aspect of a mutual interaction between two bodies.

## WORK

Work is done when a force succeeds in overcoming a body's inertia and moving the body in the direction the force is applied. The formula is

$$W = F \cdot d$$

where W is work, F is force and d is the distance moved. The amount of work done is the product of the magnitude of the force and the distance moved.

Work is measured in the English system by the foot-pound; that is, if 1 pound of force acts through a distance of 1 foot, it performs 1 foot-pound of work. In the metric CGS system, force is measured in dynes, distance is measured in centimeters, and work is denoted in ergs. An erg is the work done by a force of one dyne exerted for a distance of one centimeter. Another unit used to measure work is the joule. It is simply 10,000,000 ergs, and is equivalent to just under three-fourths of a foot-pound.

## ENERGY

Energy is defined as the ability to do work. Energy is conservative, meaning it may be neither created nor destroyed. It is defined in two forms—potential energy and kinetic energy. As its name implies, potential energy is the amount of energy that MAYBE AVAILABLE to a body due to its position. It is primarily due to the force of gravity. The higher a body is raised above the surface, the greater its POTENTIAL energy. Kinetic energy is the energy available to a body due to its motion through a field. The total amount of energy a body possesses is the sum of its potential and kinetic energies. The total amount of energy available to a body determines how much work it can accomplish.

### Force

There are two types of forces the AG deals with—contact force and action at a distance force. Contact force is the force that occurs when pressure is put on an object directly through physical contact. An example of contact force is the force your hand exerts when you push your coffee cup across a table. Contact force may act in several different directions at once as well. For example, the force exerted by water in a can is equally exerted on the sides and the bottom of the can. In addition, an upward force is transmitted to an object on the surface of the water. Forces that act through empty space without contact are known as action at a distance force. An example of this force is gravity.

### Vectors

Problems often arise that make it necessary to deal with one or more forces acting on a body. To solve problems involving forces, a means of representing forces must be found. True wind speed at sea involves two different forces and is obtained through the use of the true wind computer. Ground speed and course of aircraft are computed by adding the vector representing aircraft heading and true air speed to the vector representing the wind direction and speed. In computation of the effective fallout wind and other radiological fallout problems, the addition of forces is used. From these examples, it is evident that the addition and subtraction of forces has many applications in meteorology.

A force is completely described when its magnitude, direction, and point of application are given. A vector is a line that represents both magnitude and direction; therefore, it maybe used to describe a force. The length of the line represents the magnitude of the force. The direction of the line represents the direction in which the force is being applied. The starting point of the line represents the point of application of the force. (See fig. 2-1-1.) To represent a force of 10 pounds or 10 knots of wind acting toward due east on point A, draw a line 10 units long, starting at point A and extending in a direction of 090°.

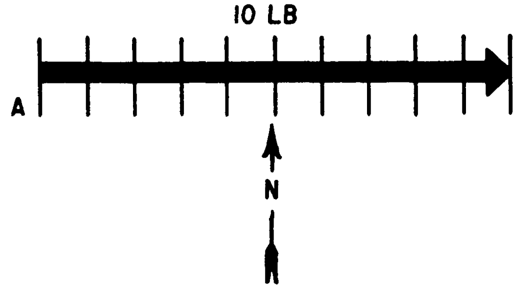


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Figure 2-1-1.—Example of a vector.

### Composition of Forces

If two or more forces are acting simultaneously at a point, the same effect can be produced by a single force of the proper size and direction. This single force, which is equivalent to the action of two or more forces, is called the resultant. Putting component forces together to find the resultant force is called composition of forces. (See fig. 2-1-2.) The vectors representing the forces must be added to find the resultant. Because a vector represents both magnitude and direction, the method for adding vectors differs from the procedure used for scalar quantities (quantities having only magnitude and no direction). To find the resultant force when a force of 5 pounds and a force of 10 pounds are applied at a right angle to point A, refer to figure 2-1-2.

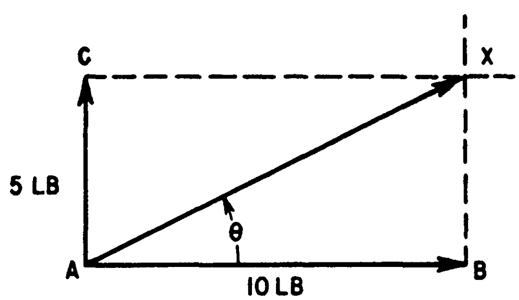


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Figure 2-1-2.—Composition of two right-angle forces.

The resultant force may be found as follows: Represent the given forces by vectors AB and AC drawn to a suitable scale. At points B and C draw dashed lines perpendicular to AB and AC, respectively. From point A, draw a line to the point of intersection X, of the dashed lines. Vector AX represents the resultant of the two forces. Thus, when two mutually perpendicular forces act on a point, the vector representing the resultant force is the diagonal of a rectangle. The length of AX, if measured on the same scale as that for the two original forces, is the resultant force; in this case approximately 11.2 pounds. The angle gives the direction of the resultant force with respect to the horizontal.

Mathematically, the resultant force of perpendicular forces can be found by using the Pythagorean theorem which deals with the solution of right triangles. The formula is $C^2 = a^2 + b^2$. This states that the hypotenuse, side "C" (our unknown resultant force) squared is equal to the sum of side "a" (one of our known forces) squared and side "b" (another of our known forces) squared.

If we substitute the known information in figure 2-1-2 we have the following:

$C^2$ = Unknown resultant force

$a^2$ = 5 lb or the known force on one side of our right triangle, side BX (same as side AC)

$b^2$ = 10 lb or the known force on the other side of our right triangle, side AB

Setting up the equation we have:

$$C^2 = a^2 + b^2$$
$$C^2 = 5^2 + 10^2$$
$$C^2 = 25 + 100$$
$$C^2 = 125$$
$$C = \sqrt{125}$$
$$C = 11.18034$$

To find the resultant of two forces that are not at right angles, the following graphic method may be used (See fig. 2-1-3.)

Let AB and AC represent the two forces drawn accurately to scale. From point C draw a line parallel to AB and from point B draw a line parallel to AC. The lines intersect at point X.

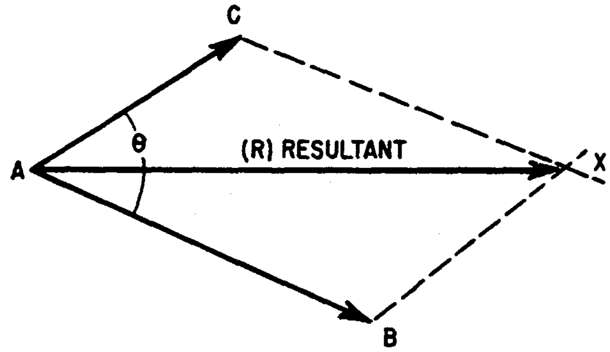


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**Figure 2-1-3.-Graphic method of the composition of forces.**

The force AX is the resultant of the two forces AC and AB. Note that the two dashed lines and the two given forces make a parallelogram ACXB. Arriving at the resultant in this manner is called the parallelogram method. The resultant force and direction of the resultant is found by measuring the length of line AX and determining the direction of line AX from the figure drawn to scale. This method applies to any two forces acting on a point whether they act at right angles or not. Note that the parallelogram becomes a rectangle for forces acting at right angles. With a slight modification, the parallelogram method of addition applies also to the reverse operation of subtraction. Consider the problem of subtracting force AC from AB. (See fig. 2-1-4.)

First, force AC is reversed in direction giving -AC (dashed line). Then, forces -AC and AB are

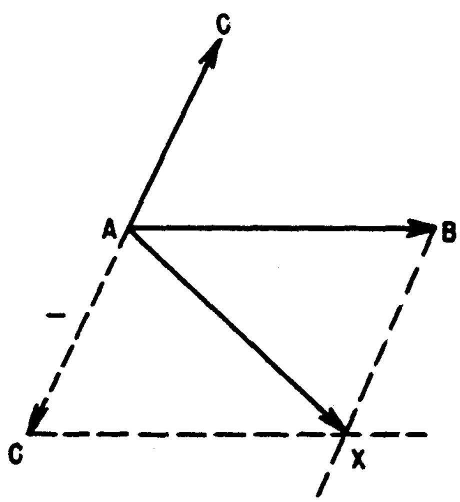


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**Figure 2-1-4.-Parallelogram method of subtracting forces.**

added by the parallelogram method, giving the resulting AX, which in this case is the difference between forces AB and AC. A simple check to verify the results consists of adding AX to AC; the sum or resultant should be identical with AB.

### Application of Vectors and Resultant Forces

The methods presented for computing vectors and resultant forces are the simplest and quickest methods for the Aerographer's Mate. There are other more complex methods described in *Mathematics, Vol. 1,* NAVEDTRA 10069-D and *Vol. II,* NAVEDTRA 10071-B.

The primary purposes of using vectors and resultant forces are for computing radiological fallout patterns and drift calculations for search and rescue operations.

# UNIT 2—LESSON 2

# MATTER

OVERVIEW

Describe how the physical properties of matter relate to the science of meteorology and identify the events that take place when matter changes state.

OUTLINE

Definitions

States of matter

Physical properties

Changes of state

## MATTER

Matter is around us in some form everywhere in our daily lives—the food we eat, the water we drink, and the air we breathe. The weather around us, such as hail, rain, invisible water vapor (humidity), etc., are all matter. Matter is present in three forms-solids, liquids, and gases. A good working knowledge of the physical properties of matter and how matter can change from one form to another can help you understand what is happening in our atmosphere that produces the various meteorological occurrences we live with every day.

**Learning Objective: Recognize how pressure, temperature, and density affect the atmosphere and describe how the gas laws are applied in meteorology.**

### DEFINITIONS

*Matter* is anything that occupies space and has weight. Two basic particles make up the composition of all matter—the *atom* and the *molecule.* The molecule is the smallest particle into which matter can be divided without destroying its characteristic properties. In physics, the molecule is the unit of matter. Molecules are composed of one or more atoms. The atom is the smallest particle of an *element* of matter that can exist either alone or in combination with others of the same or of another element. The atom and atomic structure is constantly under study and has revealed a whole new array of subatomic particles. To date, a new definition for atom has not been developed.

A *compound* is a substance (or matter) formed by combining two or more elements. Thus, ordinary table salt is a compound formed by combining two elements—sodium and chlorine. Elements and compounds may exist together without forming new compounds. Their atoms do not combine. This is known as a *mixture.* Air is a familiar mixture. Every sample of air contains several kinds of molecules which are chiefly molecules of the elements oxygen, nitrogen, and argon, together with the compounds of water vapor and carbon dioxide. Ocean water, too, is another mixture, made up chiefly of water and salt molecules, with a smaller number of molecules of many other compounds as well as molecules of several elements.

### STATES

Matter is found in all of the following three states:

1. Solid. Solids are substances that have a definite volume and shape and retain their original shape and volume after being moved from one

container to another, such as a block of wood or a stone.

2. Liquid. A liquid has a definite volume, because it is almost impossible to put it into a smaller space. However, when a liquid is moved from one container to another, it retains its original volume, but takes on the shape of the container into which it is moved. For example, if a glass of water is poured into a larger bucket or pail, the volume remains unchanged. The liquid occupies a different space and shape in that it conforms to the walls of the container into which it is poured.

3. Gas. Gases have neither a definite shape nor a definite volume. Gases not only take on the shape of the container into which they are placed but expand and fill it, no matter what the volume of the container.

Since gases and liquids flow easily, they are both called fluids. Moreover, many of the laws of physics that apply to liquids apply equally well to gases.

## PHYSICAL PROPERTIES

Since matter is anything that occupies space and has weight, it can be said that all kinds of matter have certain properties in common. These properties are inertia, mass, gravitation, weight, volume, and density. These properties are briefly covered in this section and are referred to as the general properties of matter.

### Inertia

Inertia of matter is perhaps the most fundamental of all attributes of matter. It is the tendency of an object to stay at rest if it is in a position of rest, or to continue in motion if it is moving. Inertia is the property that requires energy to start an object moving and to stop that object once it is moving.

### Mass

Mass is the quantity of matter contained in a substance. Quantity does not vary unless matter is added to or subtracted from the substance. For example, a sponge can be compressed or allowed to expand back to its original shape and size, but the mass does not change. The mass remains the same on Earth as on the sun or moon, or at the bottom of a valley or the top of a mountain. Only if something is taken away or added to it is the mass changed. Later in the unit its meaning will have a slightly different connotation.

### Gravitation

All bodies attract or pull upon other bodies. In other words, all matter has gravitation. One of Newton's laws states that the force of attraction between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between their two centers. Therefore, a mass has less gravitational pull on it at the top of a mountain than it has at sea level because the center is displaced farther away from the gravitational pull of the center of Earth. However, the mass remains the same even though the gravitational pull is different. Gravity also varies with latitude. It is slightly less at the equator than at the poles due to the equator's greater distance from the center of Earth.

### Weight

The weight of an object is a measure of its gravitational attraction. The weight depends upon the mass or quantity that it contains and the amount of gravitational attraction Earth has for it. Weight is a force, and as such it should be expressed in units of force.

Since gravity varies with latitude and height above sea level, so must weight vary with the same factors. Therefore, a body weighs more at the poles than at the equator and more at sea level than atop a mountain. In a comparison of mass and weight, mass remains constant no matter where it is, but weight varies with latitude and height above sea level.

### Volume

Volume is the measure of the amount of space that matter occupies. The volume of rectangular objects is found directly by obtaining the product of their length, width, and depth. For determining the volume of liquids and gases, special graduated containers are used.

### Density

The mass of a unit volume of a substance or mass per unit volume is called density. Usually we speak of substances being heavier or lighter than another when comparing equal volumes of the two substances.

Since density is a derived quantity, the density of an object can be computed by *dividing* its mass (or weight) by its volume. The formula for determining the density of a substance is

$$D = \frac{M}{V} \text{ (or } D = M \div V\text{)}$$

where D stands for density, M for mass, and V for volume.

From this formula, it is obvious that with mass remaining unchanged, an increase in volume causes a decrease in density. A decrease in volume causes an increase in density.

The density of gases is derived from the same basic formula as the density of a solid. Pressure and temperature also affect the density of gases. This effect is discussed later in this unit under Gas Laws.

## CHANGES OF STATE

A change of state (or change of phase) of a substance describes the change of a substance from a solid to a liquid, liquid to a vapor (or gas), vapor to a liquid, liquid to a solid, solid to vapor, or vapor to a solid. In meteorology you are concerned primarily with the change of state of water in the air. Water is present in the atmosphere in any or all of the three states (solid, liquid, and vapor) and changes back and forth from one state to another. The mere presence of water is important, but the change of state of that water in the air is significant because it directly affects the weather. The solid state of water is in the form of ice or ice crystals. The liquid state of water is in the form of raindrops, clouds, and fogs. The vapor state of water is in the form of unseen gases (water vapor) in the air.

### Heat Energy

Energy is involved in the various changes of state that occur in the atmosphere. This energy is primarily in the form of heat. Each of the changes of state processes either uses heat from the atmosphere or releases heat into the atmosphere. The heat used by a substance in changing its state is referred to as the latent heat and is usually stated in calories.

The calorie is a unit of heat energy. It is the amount of heat required to raise the temperature of 1 gram of water 1°C. A closer look at some of the major changes of state of the atmosphere helps to clarify latent heat. Refer to figure 2-2-1 during the following discussions.

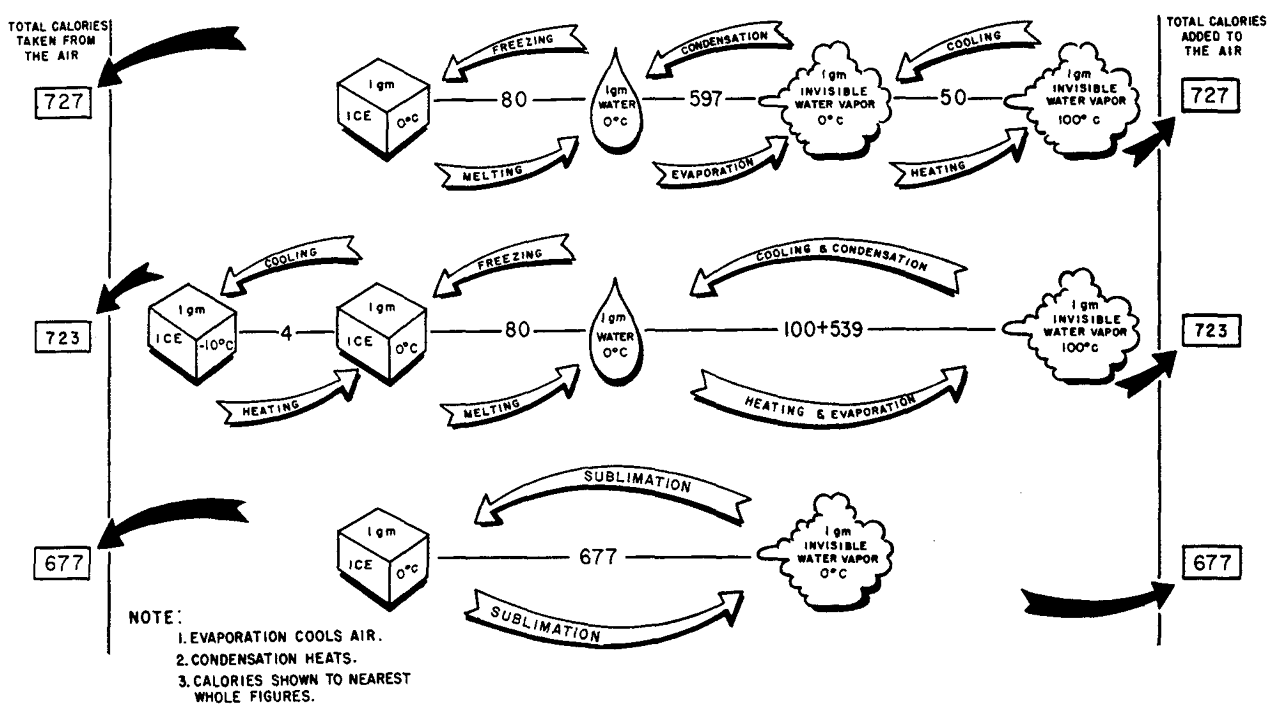


**Figure 2-2-1.—Thermal history of 1 gram of ice during changes of state.**

### Liquid To Solid and Vice Versa

Fusion is the change of state from a solid to a liquid at the same temperature. The number of gram calories of heat necessary to change 1 gram of a substance from the solid to the liquid state is known as the *latent heat* of fusion. To change 1 gram of ice to 1 gram of water at a constant temperature and pressure requires roughly 80 calories of heat. This is called the latent heat of fusion. Fusion uses heat. The source of this heat is the surrounding air.

The opposite of fusion is freezing—a liquid changes into a solid. Since it requires 80 calories to change 1 gram of ice to 1 gram of water, this same amount of heat is released into the air when 1 gram of water is changed to ice.

### Liquid To Gas and Vice Versa

Water undergoes the process of evaporation when changing from the liquid to a gaseous state. According to the molecular theory of matter, all matter consists of molecules in motion. The molecules in a bottled liquid are restricted in their motion by the walls of the container. However, on a free surface exposed to the atmosphere, the motion of the molecules in the liquid is restricted by the weight of the atmosphere or, more precisely, by the atmospheric pressure. If the speed of the liquid molecules is sufficiently high, they escape from the surface of the liquid into the atmosphere. As the temperature of the liquid is increased, the speed of the molecules is increased, and the rate at which the molecules escape from the surface also increases. Evaporation takes place only from the free or exposed surface of a substance.

During the process of evaporation, heat is released. This heat is absorbed by the water that has vaporized. The amount absorbed is approximately 539 calories per gram of water at a temperature of 100°C. On the other hand, the amount is 597.3 calories, if the evaporation takes place at a water temperature of 0°C. This energy is required to keep the molecules in the vapor state and is called the latent heat of vaporization. Since the water needs to absorb heat in order to vaporize, heat must be supplied or else evaporation cannot take place. The air provides this heat. For this reason, evaporation is said to be a cooling process, because by supplying the heat for vaporization, the temperature of the surrounding air is lowered.

Condensation is the opposite of evaporation because water vapor undergoes a change in state from gas back to liquid. However, a condition of saturation must exist before condensation can occur. That is, the air must contain all the water vapor it can hold (100 percent relative humidity) before any of it can condense from the atmosphere.

In the process of condensation, the heat that was absorbed in evaporation by the water vapor is released from the water vapor into the air and is called the latent heat of condensation. As you might expect, condensation warms the surrounding air.

### Solid To Gas and Vice Versa

Sublimation is the change of state from a solid directly to a vapor or vice versa at the same temperature. In physics and chemistry, sublimation is regarded as the change of state from solid to vapor only, but meteorologists do not make this distinction. The heat of sublimation equals the heat of fusion plus the heat of vaporization for a substance. The calories required for water to sublime are: 80 + 597.3 = 677.3, if the vapor has a temperature of 0°C.

In the sublimation process of vapor passing directly into the solid form without going through the liquid phase, the calories released are the same as those for the sublimation of a solid to a gas. Sublimation of water vapor to ice frequently takes place in the atmosphere when supercooled water vapor crystallizes directly into ice crystals and forms cirriform clouds.

# UNIT 2-LESSON 3

# GAS LAWS

OVERVIEW

Recognize how pressure, temperature, and density affect the atmosphere and describe how the gas laws are applied in meteorology.

OUTLINE

Kinetic Theory of Gases

Boyle's Law

Charles' Law

Universal Gas Law

Equation of State

Hydrostatic Equation

## GAS LAWS

Since the atmosphere is a mixture of gases, its behavior is governed by well-defined laws. Understanding the gas laws enables you to see that the behavior of any gas depends upon the variations in temperature, pressure and density.

To assist in comparing different gases and in measuring changes of gases it is necessary to have a standard or constant to measure these changes against. The standard used for gases are: a pressure of 760 millimeters of mercury (1,013.25 mb) and a temperature of 0°C. These figures are sometimes referred to as Standard Temperature and Pressure (STP).

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**Learning Objective: Recognize how pressure, temperature, and density affect the atmosphere and describe how the gas laws are applied in meteorology.**

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### KINETIC THEORY OF GASES

The Kinetic theory of gases refers to the motions of gases. Gases consist of molecules that have no inherent tendency to stay in one place as do the molecules of a solid. Instead, the molecules of gas, since they are smaller than the space between them, are free to move about. The motion is in straight lines until the lines collide with each other or with other obstructions, making their overall motion random. When a gas is enclosed, its pressure depends on the number of times the molecules strike the surrounding walls. The number of blows that the molecules strike per second against the walls remains constant as long as the temperature and the volume remain constant.

If the volume (the space occupied by the gas) is decreased, the number of blows against the wall is increased, thereby increasing the pressure if the temperature remains constant. Temperature is a measure of the molecular activity of the gas molecules and a measure of the internal energy of a gas. When the temperature is increased, there is a corresponding increase in the speed of the molecules; they strike the walls at a faster rate, thereby increasing the pressure provided the volume remains constant.

Therefore, there is a close relationship of volume, pressure, and density of gases.

### BOYLE'S LAW

Boyle's law states that the volume of a gas is inversely proportional to its pressure, provided the temperature remains constant. This means that if the volume is halved, the pressure is doubled. An example of Boyle's law is a tire pump. As the volume of the pump's cylinder is decreased by pushing the handle down, the pressure at the nozzle is increased. Another way of putting it is, as you increase the pressure in the cylinder by pushing down the handle, you also decrease the volume of the cylinder.

The formula for Boyle's law is as follows:

$$VP = V'P'$$

$V$ = initial volume

$P$ = initial pressure

$V'$ = new volume

$P'$ = new pressure

For example, assume 20 $cm^3$ of gas has a pressure of 1,000 mb. If the pressure is increased to 1,015 mb and the temperature remains constant, what will be the new volume? Applying the formula, we have

$V = 20\ cm^3$

$P = 1000$ mb

$V'$ = Unknown in $cm^3$

$P' = 1015$ mb

$$V \cdot P = V' \cdot P'$$

$$20 \cdot 1{,}000 = V' \cdot 1{,}015$$

$$20{,}000 = V' \cdot 1{,}015$$

$$V' = \frac{20{,}000}{1{,}015}$$

$$V' = 19.71\ cm^3$$

Boyle's law does not consider changes in temperature. Since our atmosphere is constantly changing temperature at one point or another, temperature must be considered in any practical application and understanding of Gas Laws.

**CHARLES' LAW**

In the section on the kinetic theory of gases, it was explained that the temperature of a gas is a measure of the average speed of the molecules of the gas. It was also shown that the pressure the gas exerts is a measure of the number of times per second that the molecules strike the walls of the container and the speed at which they strike it. Therefore, if the temperature of a gas in a closed container is raised, the speed of the molecules within the gas increases. This causes the molecules to strike the sides of the container more often per second and with more force because they are moving faster. Thus, by increasing the temperature, the pressure is increased.

Charles' law states if the volume of an enclosed gas remains constant, the pressure is directly proportional to the absolute temperature. Therefore, if the absolute temperature is doubled, the pressure is doubled; if the absolute temperature is halved, the pressure is halved. Experiments show that the volume increases by 1/273 for a 1°C rise in temperature. (Remember, 0°C is equal to 273°K.) An example of Charles' law is a bottle of soda or beer. When the soda or beer is cold, very little pressure is released when the bottle is opened. When a warm soda or beer is opened, it often results in enough pressure buildup in the bottle to squirt soda or beer out of the top. Sometimes, warm soda or beer explodes spontaneously when exposed to too much direct heat such as sunlight.

The formulas for Charles' law are as follows:

$VT' = V'T$, where pressure is assumed to be constant, and

$PT' = P'T$, where volume is constant

$V$ = initial volume

$T$ = initial temperature (absolute)

$V'$ = new volume

$T'$ = new temperature (absolute)

For example, assume that 10 $cm^3$ of a gas has a temperature of 200° absolute. If the temperature is increased to 300° absolute, what will be the new volume? Applying the formula, we have

$V = 10\ cm^3$

$T = 200°K$

$V'$ = Unknown in $cm^3$

$T' = 300°K$

$$10 \cdot 300 = V' \cdot 200$$

$$3000 = V' \cdot 200$$

$$V' = \frac{3000}{200}$$

$$V' = 15 \text{ cm}^3$$

The same type relationship can be computed by applying T´ (new temperature) and P´ (new pressure) using the formula PT´ = P´ T where the volume is assumed to remain constant.

## UNIVERSAL GAS LAW

The universal gas law is a combination of Boyle's law and Charles' law. It states that the product of the initial pressure, initial volume, and new temperature (absolute scale) of an enclosed gas is equal to the product of the new pressure, new volume, and initial temperature. The formula is as follows:

$$PVT' = P'V'T$$

P = intitial pressure

V = initial volume

T = initial temperature (absolute)

P´ = new pressure

V = new volume

T = new temperature (absolute)

For example, assume the pressure of a 500 $\text{cm}^3$ volume of gas is 600 mb and the temperature is 30°C (303° absolute). If the temperature is increased to 45°C (318° absolute) and the volume is decreased to 250 $\text{cm}^3$, what will be the new pressure of the volume? Applying the formula, we have

P = 600 mb

V = 500 $\text{cm}^3$

T = 303°K

P′ = Unknown pressure in mb

V′ = 250 $\text{cm}^3$

T′ = 318°K

$$600 \cdot 500 \cdot 318 = P' \cdot 250 \cdot 303$$

$$95{,}400{,}000 = P'75{,}750$$

$$P' = \frac{95{,}4000{,}00}{75{,}750}$$

$$P' = 1{,}259.4 \text{ mb}$$

## EQUATION OF STATE

The equation of state is a general gas law for finding pressure, temperature, or density of a dry gas. Rather than using volume, this formula uses what is called gas constant. A gas constant is a molecular weight assigned to various gases. Actually, air does not have a molecular weight because it is a mixture of gases and there is no such thing as an air molecule. However, it is possible to assign a so-called molecular weight to dry air that makes the equation of state work. The gas constant for air is 2,870 and for water vapor it is 1,800 when the pressure is expressed in millibars and the density is expressed in metric tons per cubic meter. The gas constant may be expressed differently depending on the system of units used.

The following formula is an expression of the equation of state:

$$P = \rho RT$$

P = pressure in millibars

$\rho$ = density (Greek letter rho)

R = specific gas constant

T = temperature (absolute)

The key to this formula is the equal sign that separates the two sides of the formula. This equal sign means that the same value exists on both sides; both sides of the equation are equal. If the left side of the equation (pressure) changes, a corresponding change must occur on the right side (either in the density or temperature) to make the equation equal again. Therefore, an increase of the total value on one side of the Equation of State must be accompanied by an increase of the total value on the other side. The same is true of any decrease on either side.

NOTE: Since R is a constant it will always remain unchanged in any computation.

The right side of the equation can balance out any change in either density or temperature without having a change on the left side (pressure). If, for example, an increase in temperature is made on the right side, the equation maybe kept in balance by decreasing density. This works for any value in the equation of state.

From this relationship, we can draw the following conclusions:

1. A change in pressure, density (mass or volume), or temperature requires a change in one or both of the others.

2. With the temperature remaining constant, an increase in density results in an increase in atmospheric pressure. Conversely, a decrease in density results in a decrease in pressure.

NOTE: Such a change could occur as a result of a change in the water vapor content.

3. With an increase in temperature, the pressure and/or density must change. In the free atmosphere, a temperature increase frequently results in expansion of the air to such an extent that the decrease in density outweighs the temperature increase, and the pressure actually decreases. Likewise, a temperature increase allows an increase in moisture, which in turn decreases density (mass of moist air is less than that of dry air). Couple this with expansion resulting from the temperature increase and almost invariably, the final result is a decrease in pressure.

At first glance, it may appear that pressure increases with an increase in temperature. Earlier, however, it was noted that this occurs when volume (the gas constant) remains constant. This condition would be unlikely to occur in the free atmosphere because temperature increases are associated with density decreases, or vice versa. The entire concept of the equation of state is based upon changes in density rather than changes in temperature.

## HYDROSTATIC EQUATION

The hydrostatic equation incorporates pressure, temperature, density, and altitude. These are the factors that meteorologists must also deal with in any practical application of gas laws. The hydrostatic equation, therefore, has many applications in dealing with atmospheric pressure and density in both the horizontal and vertical planes. The hydrostatic equation itself will be used in future units and lessons to explain pressure gradients and vertical structure of pressure centers. Since the equation deals with pressure, temperature, and density, it is briefly discussed here.

The hypsometric formula is based on the hydrostatic equation and is used for either determining the thickness between two pressure levels or reducing the pressure observed at a given level to that at some other level.

The hypsometric formula states that the difference in pressure between two points in the atmosphere, one above the other, is equal to the weight of the air column between the two points. There are two variables that must be considered when applying this formula to the atmosphere. They are temperature and density.

From Charles' law we learned that when the temperature increases, the volume increases and the density decreases. Therefore, the thickness of a layer of air is greater when the temperature increases. To find the height of a pressure surface in the atmosphere (such as in working up an adiabatic chart), these two variables (temperature and density) must be taken into consideration. By working upward through the atmosphere, the height of that pressure surface can be computed by adding thicknesses together. Such a set of data is available in the *Radiosonde Observation Computation Tables*, NAVWEPS 50-1D-13. Another tool for determining height and thickness of layers is the Skew-T Log P diagram covered in *AG2* Vol. 2, Unit 3.

Since there are occasions when tables and Skew-Ts are not available, a simplified version of the hypsometric formula is presented here. This formula for computing the thickness of a layer is accurate within 2 percent; therefore, it is suitable for all calculations that the Aerographer's Mate would make on a daily basis.

The thickness of a layer can be determined by the following formula:

$$Z = (49{,}080 + 107t) \cdot \frac{Po - P}{Po + P}$$

Z = altitude difference in feet (unknown thickness of layer)

49,080 = A constant (representing gravitation and height of the D-mb level above the surface)

107 = A constant (representing density and mean virtual temperature)

t = mean temperature in degrees Fahrenheit

Po = pressure at the bottom point of the layer

P = pressure at the top point of the layer

For example, let us assume that a layer of air between 800 and 700 millibars has a mean temperature of 30°F. Applying the formula, we have

$$Z = (49{,}080 + 107 \times 30) \cdot \frac{800 - 700}{800 + 700}$$

$$Z = (49{,}080 + 3{,}210) \cdot \frac{100}{1{,}500}$$

$$Z = (52{,}290) \cdot \frac{1}{15}$$

$$Z = 3{,}486 \text{ feet } (1{,}063 \text{ meters})$$

$$(1 \text{ meter} = 3.28 \text{ feet})$$

# UNIT 2—LESSON 4

# ATMOSPHERIC ENERGY

OVERVIEW

Describe the adiabatic process and determine how stability and instability affect the atmosphere.

OUTLINE

First Law of Thermodynamics

Adiabatic process

Stability and Instability

## ATMOSPHERIC ENERGY

There are two basic kinds of atmospheric energy important to AGs—kinetic and potential. Kinetic energy is energy that performs work due to *present* motion while potential energy is energy that is *stored* for later action. Kinetic energy is discussed first in relation to its effect on the behavior of gases.

According to the kinetic theory of gases, discussed in Lesson 2-3, the temperature of a gas is dependent upon the rate at which the molecules are moving about and is proportional to the kinetic energy of the moving molecules. The kinetic energy of the moving molecules of a gas is the internal energy of the gas; it follows that an increase in temperature is accompanied by an increase in the internal energy of the gas. Likewise, an increase in the internal energy results in an increase in the temperature of the gas. This relationship, between heat and energy, is called thermodynamics.

An increase in the temperature of a gas or in its internal energy can be produced by the addition of heat or by performing work on the gas. A combination of these can also produce an increase in temperature or internal energy. This is in accordance with the first law of thermodynamics.

**Learning Objective: Describe the adiabatic process and determine how stability and instability affect the atmosphere.**

## FIRST LAW OF THERMODYNAMICS

This law states that the quantity of energy supplied to any system in the form of heat is equal to work done by the system plus the change in internal energy of the system. In the application of the first law of thermodynamics to a gas, it may be said that the two main forms of energy are internal energy and work energy. Internal energy is manifested as sensible heat or simply temperature. Work energy is manifested as pressure changes in the gas. In other words, work is required to increase the pressure of a gas and work is done by the gas when the pressure diminishes. It follows that if internal energy (heat) is added to a simple gas, this energy must show up as an increase in either temperature or pressure, or both. Also, if work is performed on the gas, the work energy must show up as an increase in either pressure or temperature, or both.

An example of the thermodynamic process is a manual tire pump. The pump is a cylinder enclosed by a piston. In accordance with the first law of thermodynamics, any increase in the pressure exerted by the piston as you push down on the handle results in work being done on the air. As a consequence, either the temperature and pressure must be increased or the heat equivalent of this work must be transmitted to the surrounding bodies. In the case of a tire pump, the work done by the force on the piston is changed into an increase in the temperature and the pressure of the air. It also results in some increase in the temperature of the surrounding body by conduction.

If the surrounding body is considered to be insulated so it is not heated, there is no heat transferred. Therefore, the air must utilize this additional energy as an increase in temperature and pressure. This occurs in the adiabatic process.

## THE ADIABATIC PROCESS

The adiabatic process is the process by which a gas, such as air, is heated or cooled, without heat being added to or taken away from the gas, but rather by expansion and compression.

In the atmosphere, adiabatic and nonadiabatic processes are taking place continuously. The air near the ground is receiving heat from or giving heat to the ground. These are nonadiabatic processes. However, in the free atmosphere somewhat removed from Earth's surface, the short-period processes are adiabatic. When a parcel of air is lifted in the free atmosphere, pressure decreases. To equalize this pressure, the parcel must expand. In expanding, it is doing work. In doing work, it uses heat. This results in a lowering of temperature as well as a decrease in the pressure and density. When a parcel of air descends in the free atmosphere, pressure increases. To equalize the pressure, the parcel must contract. In doing this, work is done on the parcel. This work energy, which is being added to the parcel, shows up as an increase in temperature. The pressure and density increase in this case also.

### Terms

In discussing the adiabatic process several terms are used that you should understand.

**LAPSE RATE.—** In general, lapse rate is the rate of decrease in the value of any meteorological element with elevation. However, it is usually restricted to the rate of decrease of temperature with elevation; thus, the lapse rate of the temperature is synonymous with the vertical temperature gradient. The temperature lapse rate is usually positive, which means that the temperature decreases with elevation.

**INVERSION.—** Inversions describe the atmospheric conditions when the temperature increases with altitude, rather than decreases as it usually does. Inversions result from the selective absorption of Earth's radiation by the water vapor in the air, and also from the sinking, or subsidence, of air, which results in its compression and, therefore, heating. Either effect alone may cause an inversion; combined, the inversion is stronger.

When air is subsiding (sinking), the compressed air heats. This frequently produces a subsidence inversion. When subsidence occurs above a surface inversion, the surface inversion is intensified. Such occurrences are common in wintertime high-pressure systems. The air in the inversion layer is very stable, and the cold air above the inversion acts as a lid trapping fog, smoke, and haze beneath it. Poor visibility in the lower levels of the atmosphere results, especially near industrial areas. Such conditions frequently persist for days, notably in the Great Basin region of the western United States.

An inversion is a frequent occurrence (especially at night) in the Tropics and in the Polar regions. For night conditions all over the world, polar and tropical regions included, it may be said that low-level inversions are the rule rather than the exception.

**ISOTHERMAL.—** In the isothermal lapse rate, no cooling or warming is noted and the rate is neutral with height—no change in temperature with height.

### Adiabatic Heating and Cooling

Air is made up of a mixture of gases that is subject to adiabatic heating when it is compressed and adiabatic cooling when it is expanded. As a result, air rises seeking a level where the pressure of the body of air is equal to the pressure of the air that surrounds it. There are other ways air can be lifted, such as through the thermodynamic processes of a thunderstorm or mechanically, such as having colder, denser air move under it or by lifting as it flows up over a mountain slope.

As the air rises, the pressure decreases allowing the parcel of air to expand. This continues until it reaches an altitude where the pressure and density are equal to its own. As it expands, it cools through a thermodynamic process in which there is no transfer of heat or mass across the boundaries of the system in which it operates (adiabatic process). As air rises, it cools because it expands by moving to an altitude where pressure and density is less. This is called adiabatic cooling. When the process is reversed and air is forced downward, it is compressed, causing it to heat. This is called adiabatic heating, (See fig. 2-4-1.)

Remember, in an adiabatic process an increase in temperature is due only to COMPRESSION when the air sinks or subsides. A decrease in temperature is due only to EXPANSION when air rises, as with convective currents or air going over mountains. There is no addition or subtraction of heat involved. The changes in temperature are due to the conversion of energy from one form to another.

## STABILITY AND INSTABILITY

The atmosphere has a tendency to resist vertical motion. This is known as stability. The normal flow of air tends to be horizontal. If this flow is disturbed, a stable atmosphere resists any upward or downward displacement and tends to return quickly to normal horizontal flow. An unstable atmosphere, on the other hand, allows these upward and downward disturbances to grow, resulting in rough (turbulent) air. An example is the towering thunderstorm that grows as a result of a large intense vertical air current.

Atmospheric resistance to vertical motion (stability), depends upon the vertical distribution of the air's weight at a particular time. The weight varies with air temperature and moisture content.

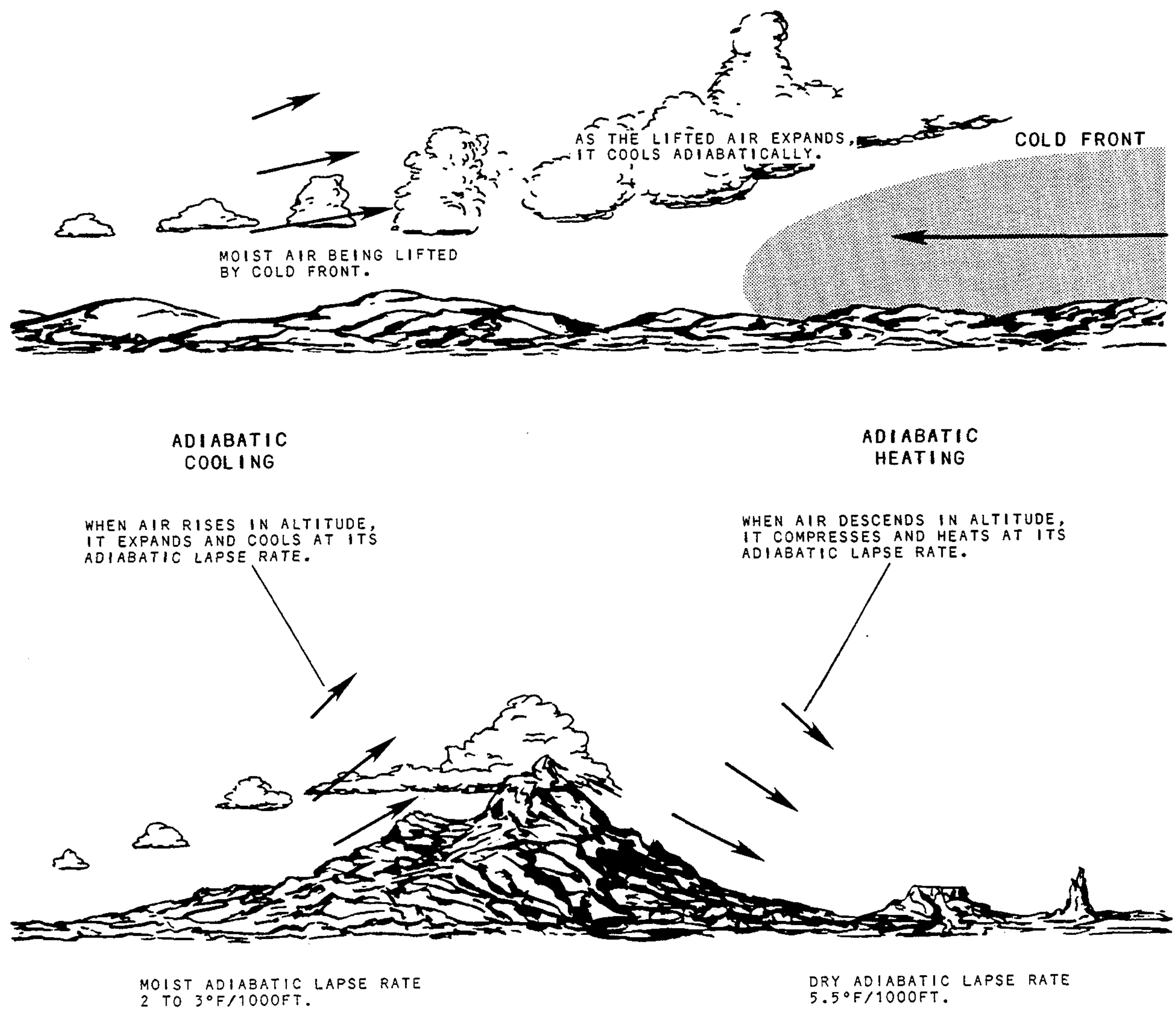


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Figure 2-4-1.—Adiabatic cooling and heating process.

As shown in figure 2-4-2, in comparing two parcels of air, hotter air is lighter than colder air; and moist air is lighter than dry air. If air is relatively warmer or more moist than it's surroundings, it is forced to rise and is unstable. If the air is colder or dryer than its surroundings, it sinks until it reaches its equilibrium level and is stable. The atmosphere can only be at equilibrium when light air is above heavier air-just as oil poured into water rises to the top to obtain equilibrium. The stability of air depends a great deal on temperature distribution and to a lesser extent on moisture distribution.

Since the temperature of air is an indication of its density, a comparison of temperatures from one level to another can indicate how stable or unstable a layer of air might be—that is, how much it tends to resist vertical motion.

**Lapse Rates**

In Unit 1, it was shown that temperature usually decreases with altitude and that the rate at which it decreases is called the lapse rate. The lapse rate, commonly expressed in degrees Fahrenheit per 1,000 feet, gives a direct measurement of the atmosphere's resistance to vertical

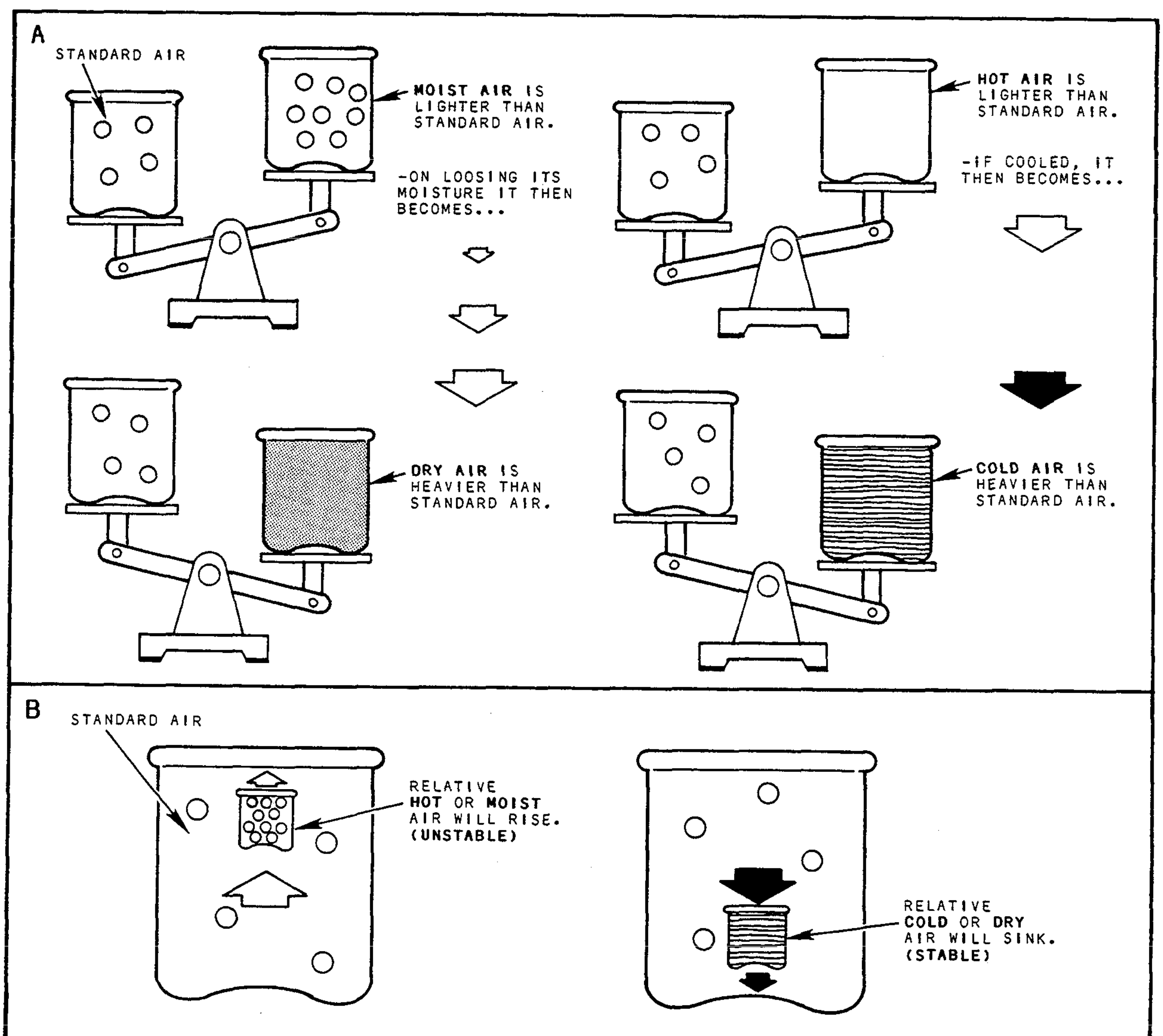


**Figure 2-4-2.—Moisture content and temperature determines weight of air.s**

motion. The degree of stability of the atmosphere may vary from layer to layer as indicated by changes of lapse rate with height. (See table 2-4-1 and fig. 2-4-3.)

**DRY ADIABATIC LAPSE RATE.—** If a parcel of air is lifted, its pressure is DECREASED, since pressure decreases with height, and its temperature falls due to the expansion. If the air is dry and the process is adiabatic, the rate of temperature fall is 1°C per 100 meters of lift (10°C per Km), or 5 1/2°F per 1,000 feet of lift. If that parcel descends again to higher pressure, its temperature then INCREASES at the rate of 1°C

**Table 2-4-1.–Lapse rates of temperature**

| Lapse rate | Per 1,000 feet | Per 100 meters |
|---|---|---|
| Dry adiabatic | 5 1/2°F | 1°C |
| Saturation (moist) adiabatic | 2-3°F | .55°C |
| Average | 3.3°F | .65°C |
| Superadiabatic | 5 1/2-15°F | 1-3.42°C |
| Autoconvective | More than 15°F | More than 3.42°C |

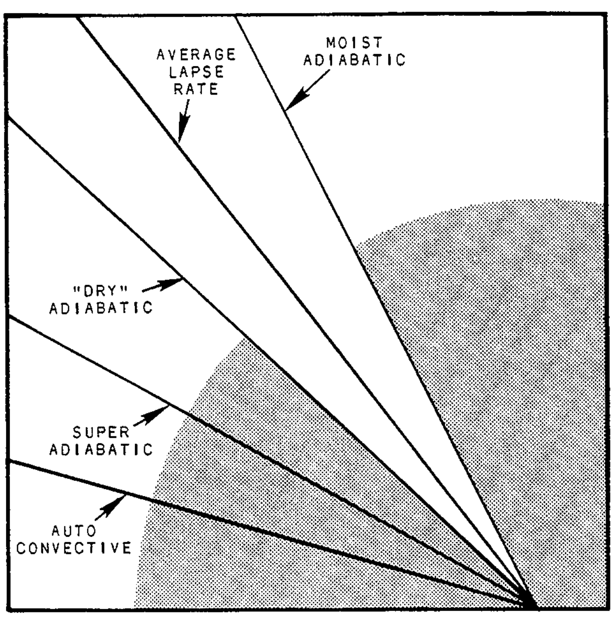


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**Figure 2-4-3.—Adiabatic lapse rates.**

per 100 meters or 5 1/2°F per 1,000 feet. This is known as the dry adiabatic lapse rate.

**MOIST (SATURATION) ADIABATIC LAPSE RATE.—** When a mass of air is lifted, it cools at the dry adiabatic lapse rate of 5 1/2°F per 1,000 feet as long as it remains unsaturated (relative humidity below 100 percent). If the original moisture is being carried along with the mass as it ascends and it cools to its saturation temperature, the relative humidity reaches 100 percent. Condensation takes place with further cooling. For each gram of water condensed, about 597 calories of heat are liberated. This latent heat of condensation is absorbed by the air, and the adiabatic cooling rate is decreased to 2° to 3°F per 1,000 feet instead of 5 1/2°F per 1,000 feet. The process during the saturated expansion of the air is called the saturation adiabatic, the moist adiabatic, or the pseudoadiabatic process. The pseudoadiabatic process assumes that moisture falls out of the air as soon as it condenses.

How the temperature of a parcel of air changes in response to these processes was illustrated in Unit 1 and because of its importance, it is illustrated again now. Assume that a saturated parcel of air having a temperature of 44°F is at 5,000 feet and is forced over a 12,000-foot mountain. Condensation occurs from 5,000 to 12,000 feet so that the parcel cools at the moist adiabatic rate (3°F per 1,000 ft) and reaches a temperature of approximately 23°F at the top of the mountain. Assuming that the condensation in the form of precipitation has fallen out of the air during the ascent, the parcel heats at the dry adiabatic rate as it descends to the other side of the mountain. When it reaches the 5,000-foot level, the parcel has descended 7,000 feet at a rate of 5 1/2°F per 1,000 feet. This results in an increase of 38.5°F. Adding the 38.5°F increase to the original 12,000 feet temperature of 23°F, the parcel has a new temperature of 61.5°F.

**AVERAGE ADIABATIC LAPSE RATE.—** The average lapse rate lies between the dry adiabatic and the moist adiabatic at about 3.3°F per 1,000 feet.

**SUPERADIABATIC LAPSE RATE.—** The superadiabatic lapse rate is a decrease in temperature of more than 5 1/2°F per 1,000 feet and less than 15°F per 1,000 feet.

**AUTOCONVECTIVE LAPSE RATE.—** The autoconvective lapse rate is the decrease of more than 15°F per 1,000 feet. This lapse rate is rare and is usually confined to shallow layers.

### Types of Stability

In figure 2-4-4 a bowl is set on a flat surface with a ball placed inside it. The ball rests in the bottom of the bowl; but, if you push the ball in any direction, it seeks out the bottom of the bowl again. This is referred to as ABSOLUTE STABILITY (A in fig. 2-4-4). Turn the bowl upside down, position the ball anywhere on the bowl's bottom surface (B in fig. 2-4-4) and the ball starts moving on its own without any other force being applied. This is a condition of ABSOLUTE INSTABILITY. If you now remove the bowl and place the ball on the flat surface (C in fig. 2-4-4), you have NEUTRAL STABILITY—that is, if a force is applied to the ball, it moves; but if the force is removed, the ball stops.

Air in the atmosphere reacts in a similar manner when moved up or down. If it is moved up and becomes more dense than the surrounding air, it returns to its original position and is considered STABLE. If it becomes less dense than the surrounding air, it continues to rise and is considered UNSTABLE. When density remains the same as the surrounding air after being lifted, it is considered NEUTRALLY STABLE, with no tendency to rise or sink.

### Equilibrium of Dry Air

The method used for determining the equilibrium of air is the parcel method, wherein a parcel of air is lifted and then compared with the surrounding air to determine its equilibrium. The dry adiabatic lapse rate is always used as a reference to determine the stability or instability of dry air (the parcel).

**ABSOLUTE INSTABILITY.—** Consider a column of air in which the actual lapse rate is

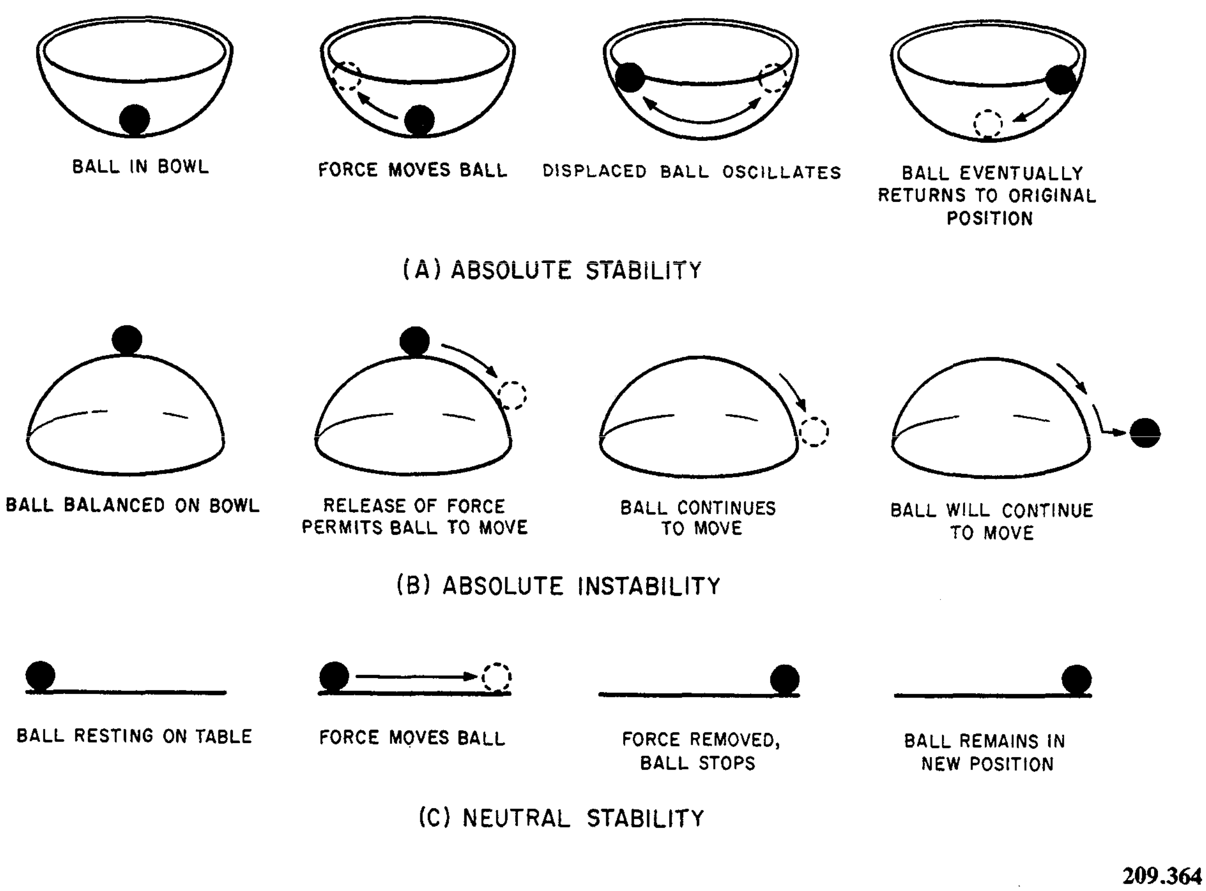


**Figure 2-4-4.—Analogy depiction of stability.**

greater than the dry adiabatic lapse rate. The actual lapse rate is to the left of the dry adiabatic lapse rate on the Skew-T diagram (fig. 2-4-5). If the parcel of air at point A is displaced upward to point B, it cools at the dry adiabatic lapse rate. Upon arriving at point B, it is warmer than the surrounding air. The parcel therefore has a tendency to continue to rise, seeking air of its own density. Consequently the column becomes unstable. From this, the rule is established that if the lapse rate of a column of air is greater than the dry adiabatic lapse rate, the column is in a state of ABSOLUTE INSTABILITY. The term absolute is used because this applies whether the air is dry or saturated, as is evidenced by displacing upward a saturated parcel of air from point A along a saturation adiabat to point B. The parcel is more unstable than if displaced along a dry adiabat.

**STABILITY.—** Consider a column of dry air in which the actual lapse rate is less than the dry adiabatic lapse rate. The actual lapse rate is to the right of the dry adiabatic lapse rate on the Skew-T diagram (fig. 2-4-6). If the parcel at point A were displaced upward to point B, it would cool at the dry adiabatic lapse rate; and upon arriving at point B, it would be colder than the surrounding air. It would, therefore, have a tendency to return to its original level. Consequently, the column of air becomes stable. From this, the rule is established that if the actual lapse rate of a column of DRY AIR is less than the dry adiabatic lapse rate, the column is stable.

**NEUTRAL STABILITY.—** Consider a column of DRY AIR in which the actual lapse rate is equal to the dry adiabatic lapse rate. The parcel cools at the dry adiabatic lapse rate if displaced upward. It would at all time be at the same temperature and density as the surrounding air. It also has a tendency neither to return to nor to move farther away from its original position. Therefore, the column of dry air is in a state of NEUTRAL STABILITY.

### Equilibrium of Saturated Air

When saturated air is lifted, it cools at a rate different from that of dry air. This is due to release of the latent heat of condensation, which is absorbed by the air. The rate of cooling of moist air is known as the saturation adiabatic lapse rate. This rate is used as a reference for determining the equilibrium of saturated air.

**ABSOLUTE STABILITY.—** Consider a column of air in which the actual lapse rate is less than the saturation adiabatic lapse rate. The actual lapse rate is to the right of the saturation adiabatic lapse rate on the Skew T diagram (fig. 2-4-7). If the parcel of saturated air at point A is displaced upward to point B, it cools at the saturation adiabatic lapse rate. The air upon arriving at point B becomes colder than the surrounding air. The layer, therefore, would be in a state of ABSOLUTE STABILITY. From this, the following rule is established: If the actual lapse rate for a column of air is less than the saturation adiabatic lapse rate, the column is absolutely

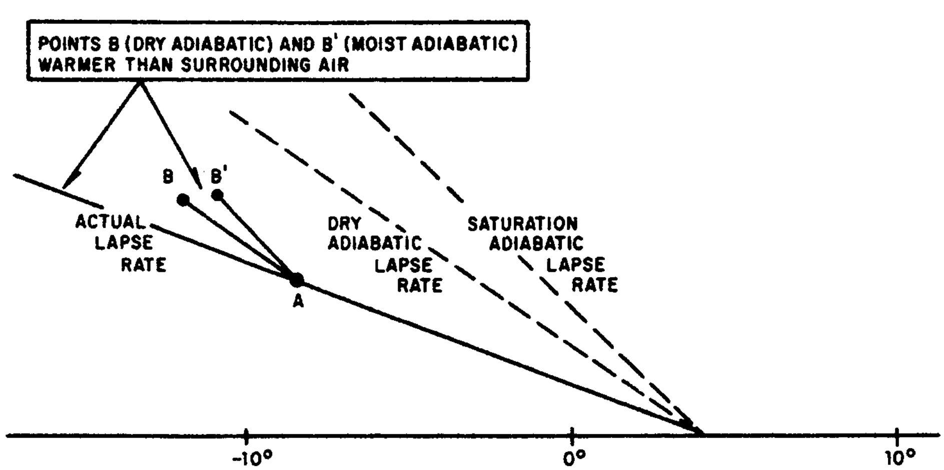


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Figure 2-4-5.—Absolute instability (any degree of saturation).

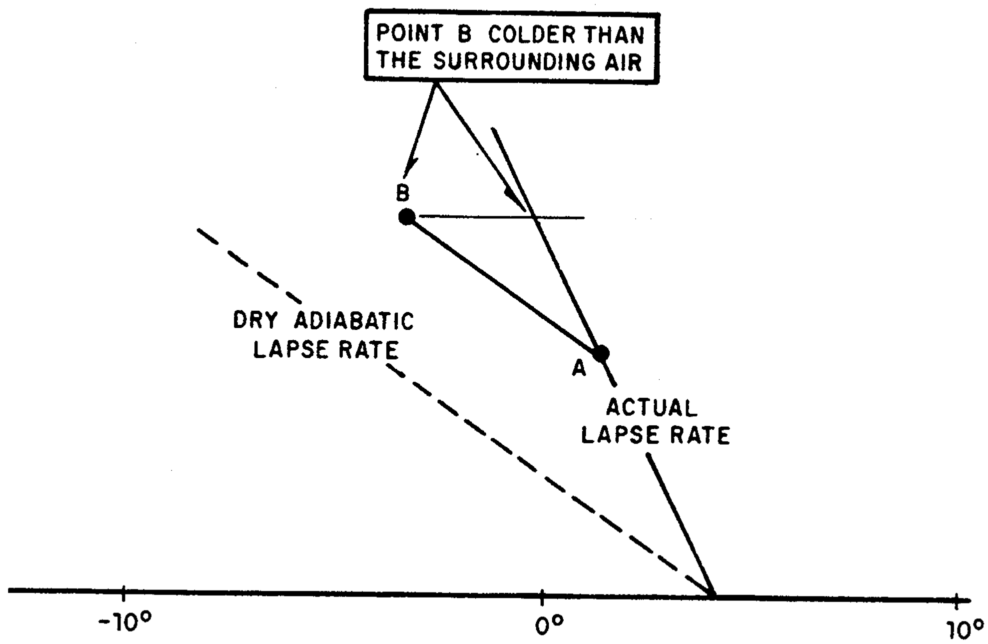


Figure 2-4-6.—Stability (dry air).

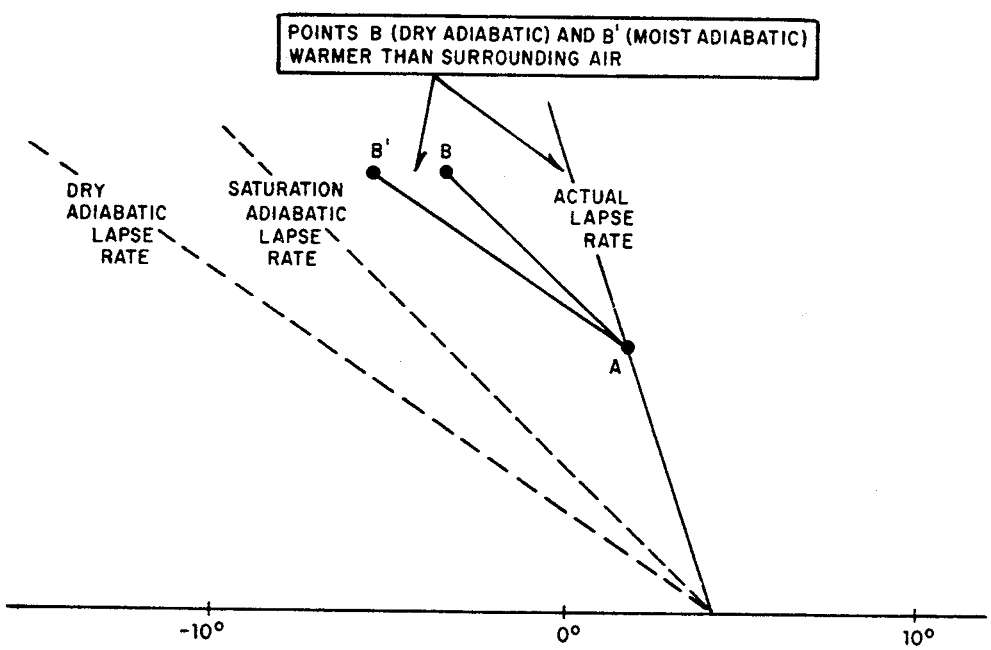


Figure 2-4-7.—Absolute stability (any degree of saturation).

stable and the parcel would return to its original position. Dry air cools dry adiabatically and is also colder than the surrounding air. Therefore, this rule applies to all air, as is evidenced when an unsaturated parcel of air is displaced upward dry adiabatically to point B. Here, the parcel is more stable than the parcel displaced along a saturation adiabat.

**INSTABILITY.—** Consider now a column of air in which the actual lapse rate is greater than the saturation adiabatic lapse rate (fig. 2-4-8). If a parcel of moist air at point A is displaced upward to point B, it cools at the saturation adiabatic lapse rate. Upon arriving at point B the parcel is then warmer than the surrounding air. For this reason, it has a tendency to continue moving farther from its original position. The parcel, therefore, is in a state of INSTABILITY. The following rule is applicable. If the actual lapse rate for a column of SATURATED (MOIST) AIR is greater than the saturation adiabatic lapse rate, the column is unstable.

**NEUTRAL STABILITY.—** Consider a column of saturated air in which the actual lapse rate is equal to the saturation adiabatic lapse rate. A parcel of air displaced upward cools at the saturation adiabatic lapse rate and is at all times equal in temperature to the surrounding air. On that account, it tends neither to move farther away from nor to return to its original level. Therefore, it is in a state of NEUTRAL STABILITY. The rule for this situation is that if the actual lapse rate for a column of saturated air is equal to the saturation adiabatic lapse rate, the column is neutrally stable.

### Conditional Instability

In the treatment of stability and instability so far, only air that was either dry or saturated was considered. Under normal atmospheric conditions natural air is unsaturated to begin with, but becomes saturated if lifted high enough. This presents no problem if the actual lapse rate for the column of air is greater than the dry adiabatic lapse rate (absolutely unstable) or if the actual lapse rate is less than the saturation adiabatic lapse rate (absolutely stable). However, if the lapse rate for a column of natural air lies between the dry adiabatic lapse rate and the saturation adiabatic lapse rate, the air may be stable or unstable, depending upon the distribution of moisture. When the actual lapse rate of a column of air lies between the saturation adiabatic lapse rate and the dry adiabatic lapse rate, the equilibrium is termed CONDITIONAL INSTABILITY, because the stability is conditioned by the moisture distribution. The equilibrium of this column of air is determined by the use of positive and negative energy areas as analyzed on a Skew-T,

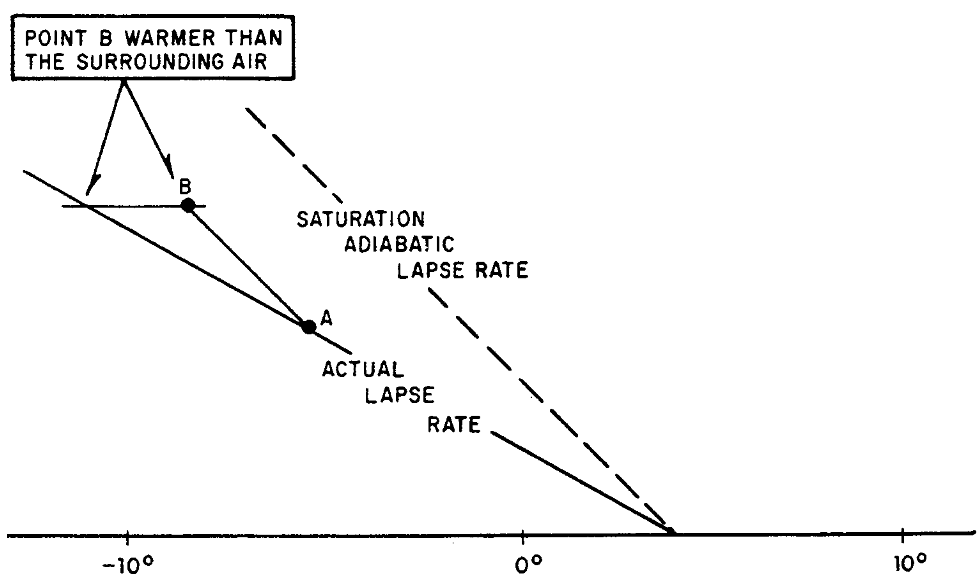


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**Figure 2-4-8.—Instability (saturated air).**

Log P diagram. The determination of an area as positive or negative depends upon whether the parcel is being lifted mechanically (by a front or orographic barriers) or by convective means and whether the environment is colder or warmer than the ascending parcel. Positive areas are conducive to instability. Negative areas are conducive to stability.

**TYPES OF CONDITIONAL INSTABILITY.—** Conditional instability may be one of three types. The REAL LATENT type is a condition in which the positive area is larger than the negative area (potentially unstable). The PSEUDOLATENT type is a condition in which the positive area is smaller than the negative area (potentially STABLE). The STABLE type is a condition in which there is no positive area.

NOTE: The computing of positive and negative energy areas and Skew-T analysis is covered in detail in *AG2,* Vol. 2, Unit 3. Figure 2-4-9

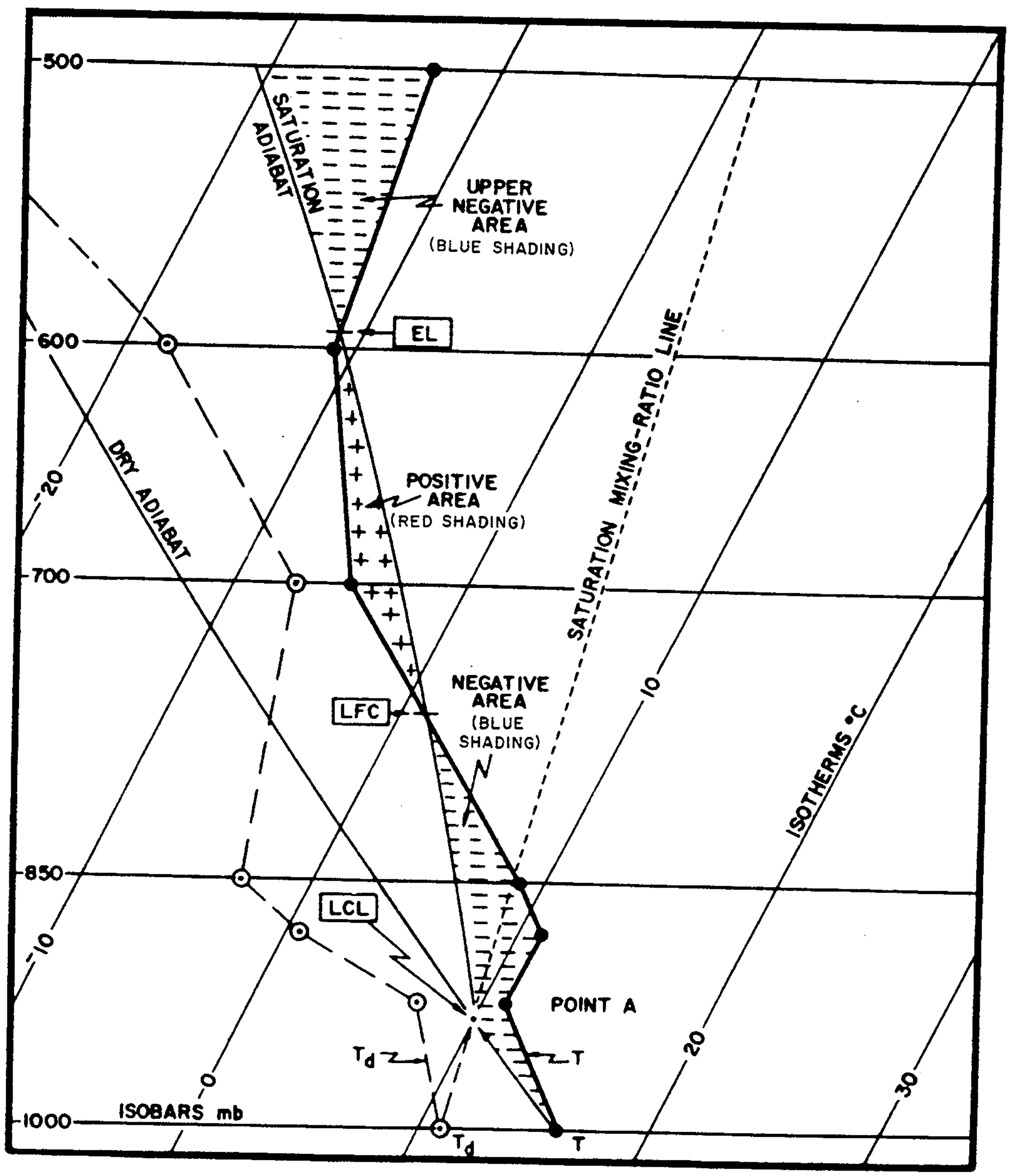


Figure 2-4-9.—Example of positive and negative energy areas (mechanical lifting). 305.43

shows an example of analyzed positive and negative energy areas as they would appear on a Skew-T, Log P diagram.

### Autoconvection

AUTOCONVECTION is a condition started spontaneously by a layer of air when the lapse rate of temperature is such that density increases with elevation. For density to increase with altitude, the lapse rate must be equal to or exceed 3.42°C per 100 meters. (This is the AUTOCONVECTIVE LAPSE RATE.) An example of this condition is found to exist near the surface of the earth in a road mirage or a dust devil. These conditions occur over surfaces that are easily heated, such as the desert, open fields, etc.; they are usually found during periods of intense surface heating.

### Convection Stability and Instability

In the discussion so far of convection stability and instability, PARCELS of air have been considered. Let us now examine LAYERS of air. A layer of air that is originally stable may become unstable due to moisture distribution if the entire layer is lifted.

Convective stability is the condition that occurs when the equilibrium of a layer of air, because of the temperature and humidity distribution, is such that when the entire layer is lifted, its stability is increased (becomes more stable).

Convective instability is the condition of equilibrium of a layer of air occurring when the temperature and humidity distribution is such that when the entire layer of air is lifted, its instability is increased (becomes more unstable).

**CONVECTIVE STABILITY.—** Consider a layer of air whose humidity distribution is dry at the bottom and moist at the top. If the layer of air is lifted, the top and the bottom cool at the same rate until the top reaches saturation. Thereafter, the top cools at a slower rate of speed than the bottom. The top cools saturation adiabatically (.55°c/100 meters), while the bottom continues to cool dry adiabatically (1°c/100 meters). The lapse rate of the layer then decreases; hence, the stability increases. The layer must be initially unstable and may become stable when lifting takes place.

**CONVECTIVE INSTABILITY.—** Consider a layer of air in which the air at the bottom is moist and the air at the top of the layer is dry. If this layer of air is lifted, the bottom and the top cool dry adiabatically until the lower portion is saturated. The lower part then cools saturation adiabatically while the top of the layer is still cooling dry adiabatically. The lapse rate then begins to increase and instability increases.

To determine the convective stability or instability of a layer of air, you should first know why you expect the lifting of a whole layer. The obvious answer is an orographic barrier or a frontal surface. Next, determine how much lifting is to be expected and at what level it commences. Lifting of a layer of air close to the surface of the Earth is not necessary. The amount of lifting, of course, depends on the situation at hand. Figure 2-4-10 illustrates the varying degrees of air stability that are directly related to the rate at which the temperature changes with height.

### Determining Bases of Convective Type Clouds

You have seen from our foregoing discussion that moisture is important in determining certain

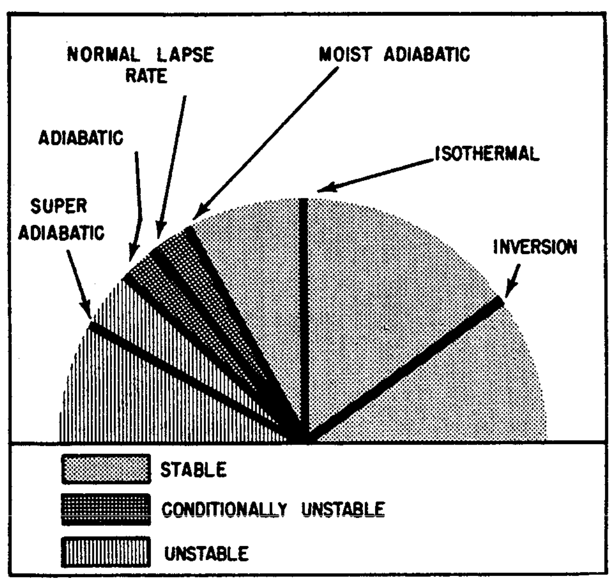


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**Figure 2-4-10.—Degrees of stability in relation to temperature changes with height.**

stability conditions in the atmosphere. You know, too, that the difference between the temperature and the dewpoint is an indication of the relative humidity. When the dewpoint and the temperature are the same, the air is saturated and some form of condensation cloud may be expected. This lends itself to a means of estimating the height of the base of clouds formed by surface heating when the surface temperature and dewpoint are known. You know that the dewpoint decreases in temperature at the rate of 1°F per 1,000 feet during a lifting process. The ascending parcel in the convective current experiences a decrease in temperature of about 5 1/2°F per 1,000 feet. Thus the dewpoint and the temperature approach each other at the rate of 4 1/2°F per 1,000 feet. As an example, consider the surface temperature to be 80°F and the surface dewpoint 62°F, a difference of 18°F. This difference, divided by the approximate rate the temperature approaches the dewpoint (4 1/2°F per 1,000 ft) indicates the approximate height of the base of the clouds caused by this lifting process (18 ÷ 4 1/2) x 1000 = 4,000 feet). This is graphically shown in figure 2-4-11.

This method cannot be applied to all cloud types. It is limited to clouds formed by convection currents, such as summertime cumulus clouds, and only in the locality where the clouds form. It is not valid around maritime or mountainous areas.

### Stability in Relation to Cloud Type

The degree of stability of the atmosphere helps to determine the type of clouds formed. For example, figure 2-4-12 shows that if *stable* air is forced to ascend a mountain slope, clouds will be layerlike with little vertical development and little or no turbulence. *Unstable air,* if forced to ascend the slope, causes considerable vertical development and turbulence in the clouds. The base of this type of cloud can be determined by mechanical lifting as analyzed on a Skew-T.

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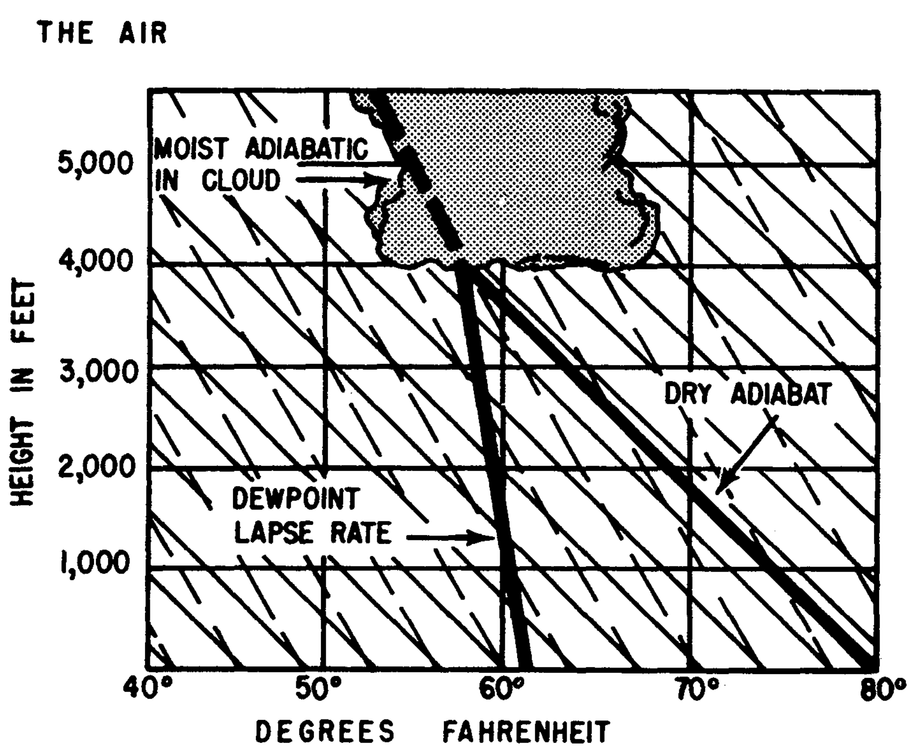


**Figure 2-4-11.—Determination of cloud's base when the dewpoint and temperature are known.**

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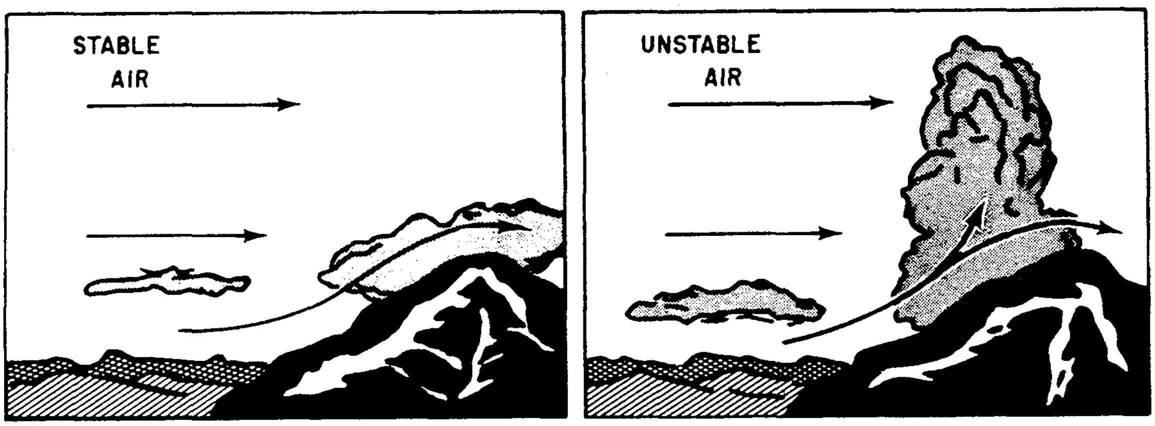


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**Figure 2-4-12.—Illustration showing that very stable air retains its stability ever when it is forced upward, forming a flat cloud. Air which is potentially unstable when forced upward becomes turbulent and forms a towering cloud.**